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METHODS FOR CALIBRATING STANDARD-SIGNAL GENERATORS

Gustavus A. Morgan, Jr.

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Approved by:

F. M. Gager, Head, Special Research Branch
Dr. R. M. Page, Superintendent, Radio Division III

NAVAL RESEARCH LABORATORY
CAPTAIN F. R. FURTH, USN, DIRECTOR
WASHINGTON, D.C.

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ABSTRACT

An investigation was made of the problems involved in calibrating standard-signal generators. Signal leakage and several methods for detecting it were studied, since the determination of this leakage is required for accurate calibration. Although reliable information from a number of sources were compiled, it was concluded that no available single method of calibration was suitable for all instruments. As far as possible, all known methods for calibrating signal generators were studied to determine if any worth-while improvements in any existing methods appeared possible. Some attempts were made to develop different methods, but no significant results were obtained.

PROBLEM STATUS

This is a final report on one phase of the problem; work on the problem is continuing.

AUTHORIZATION

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METHODS FOR CALIBRATING STANDARD-SIGNAL GENERATORS

INTRODUCTION

The general problem proposed by the Bureau of Aeronautics was to develop a method and necessary equipment for calibration of signal generators. Since there were no specified limits on the types of signal generators to be calibrated, there were no restrictions on frequency or types of modulation.

A study of available signal generators indicated that no single method of calibration was suitable for all instruments. As far as possible, all known methods for calibrating signal generators were studied to determine if any worth-while improvement in any existing method appeared possible. To a degree, some attempt was made to develop different methods but no significant results were obtained.

Therefore, a compilation was made of information about existing signal-generator calibration which is in accordance with the request of the Bureau of Aeronautics. Useful methods were analyzed in detail, to show the limitations, advantages, and disadvantages of each method.

DEFINITIONS

The term signal generator designates any of a large group of instruments which develop a signal usually intended to simulate a signal produced by a distant transmitter. These instruments are used primarily in laboratory tests and adjustment of receivers. Many are inherently unsuitable for calibration of the output level. The instruments which may be calibrated are a special group known as standard-signal generators. These instruments may differ greatly in details of design, but as a class, all meet the same general requirements. Reference to a signal generator implies an instrument meeting the following requirements:

1. By use of adequate shielding and filtering, the instrument is designed so that the signal appears only at output terminals, which may be binding posts, a coaxial jack, coaxial cable, or waveguide, as required for the signal frequency.

2. Some form of indicator is provided to measure the output and means are included for adjusting the output signal level to desired values.

3. Means for controlling the frequency of the signal are ordinarily included. The design usually insures that the frequency is reasonably stable.

4. Means are often included to apply desired types of modulation to the signal and to measure and control the degree of modulation.

Complete calibration of a signal generator requires measurement of all characteristics of the output signal. These include such qualities as frequency, stability of frequency, type and degree of desired and undesired modulation, and amplitude or power of the signal, as well as output impedance, signal leakage, and possibly many other factors. However, instruments and techniques have been developed for accurate measurement of all features except signal level and signal leakage. This investigation therefore, is primarily concerned with measurement of these two factors.

In this study, reference to calibration of signal generators, signal level is understood to mean measurement of the true output voltage or power and comparison of the true value with the value indicated by the signal-generator internal indicator.

Signal leakage may be defined as the appearance, external to the signal generator, of any signal produced by the r-f source in the generator which has not passed through the metering (output) system of the generator.

INSTRUMENT REQUIREMENTS FOR CALIBRATION

A study of available signal generators was made to determine the manufacturer's or service specifications. Instruments are available which produce (a) output frequencies extending from 5 kilocycles to microwave frequencies, (b) output levels from approximately 0.1 microvolt to 10 volts, and (c) output impedances from 0.75 ohm to about 100 ohms.

The specified accuracy of the indicated, signal-output level was found to be between 8 percent and 20 percent. This means that the true output level may be greater or smaller than the indicated value by the percentage shown.

The ideal instrument for signal-generator calibration thus appears to be a radio-frequency voltmeter which responds equally to all frequencies above 5 kilocycles. It should be sensitive enough to measure a signal of as low a value as 0.1 microvolt but should have a wide enough range to indicate 10 volts. The accuracy should be somewhat greater than ± 8 percent, probably in the order of ± 4 percent; it preferably should be untuned and capable of calibration in terms of dc values; and the input impedance should be infinite. However, the prospect for developing such an instrument appears rather remote.

Associated with the voltmeter in some measurements should be a variable impedance which can be adjusted to match impedances of 30 to 100 ohms at any frequency above 5 kilocycles. Compliance with this requirement is also unlikely.

SOURCES OF SIGNAL-GENERATOR CALIBRATION ERRORS

Signal generators are calibrated in the process of manufacture and require recalibration as a part of maintenance, because of discrepancies in measurements, or to confirm validity of measurements. It is of interest to analyze the sources of error in signal generator output values in order to determine the most suitable methods and instruments for calibration.

There appear to be five major sources of inaccuracies in the signal-generator output. Any combination of these causes may occur in individual signal generators. These are:

1. Improper use of the signal generator.

2. Inaccuracy of the signal-generator output indicator or monitor.

3. Inaccuracy of the signal-generator output attenuator.

4. Improper impedance of output cable and/or load.

5. Signal leakage.

The first factor is included because many signal generators appear to be inaccurate, as indicated by discrepancies in measurements, but the error is actually due to failure to consider all design requirements of the signal generator or to misinterpretation of results. These same errors may occur in calibration.

In all modern signal generators, the input to a calibrated, adjustable attenuator is standardized at some selected, relatively high voltage which is indicated directly by some form of meter. An attenuator then reduces this high-level to the desired low-level output. The input to the attenuator is usually chosen to be some particular value which permits calibrating the attenuator directly in microvolts, or in decibels with reference to a specific standard value.

Some signal generators are calibrated in terms of the open-circuit voltage at the output terminals while others are calibrated in terms of the voltage developed across a specified load impedance connected to the output terminals. Other signal generators are calibrated in terms of available power—maximum power which the signal generator can deliver to a load at any given attenuator setting. This power is actually delivered only to a load which matches the generator internal impedance.

Signal generators producing sinusoidal signals are calibrated in rms values of voltage or in average power. Generators producing pulsed signals may be calibrated in terms of average or peak power.

The four principal types of output indicator and attenuator connections found in modern signal generators are shown in Figure 1. A generator using the circuit illustrated in Figure 1A is usually calibrated in terms of open-circuit voltage. One signal generator using this circuit is the General Radio Model 1001-A. Generators using the circuit shown in Figure 1B, such as the General Radio Model 805-G or the Ferris Model 16C, are also calibrated in terms of open-circuit voltage.

The circuit shown in Figure 1C is adjusted by reducing the attenuation to a low value and then varying the input to the attenuator to obtain the desired standard indication on the output meter. The attenuator may be set at a selected calibration point (such as 0.1 volt) for standardization, or a variable index may be set in position after the output is standardized. This circuit does not permit continuous monitoring of the input to the attenuator. Some generators do not include an impedance at the indicated point, but standardize the output voltage with the desired load impedance connected to the output terminals, resulting in a generator having effectively zero impedance. In other models, such as the General Radio Model 1021-A, an impedance is connected at the indicated points.

The circuit shown in Figure 1D is a general circuit which has many variations of minor details in different signal generators. The r-f output inductance may actually be the r-f oscillator coil while the attenuator input coil may not be physically present. The relation between the voltage induced in the sampling probe and that induced in the attenuator is determined by calibration. The sampling probe and the attenuator input circuit are usually variable as a mechanical unit with respect to the r-f source. The r-f voltmeter is generally a bolometer in a bridge circuit which is balanced only when the desired standard voltage is induced in the attenuator input. The index marker of the attenuator is usually moved to position after the input is standardized. The Measurements Corp. Model 80 is one type of generator using this circuit, and the General Radio Model 1022-A has a similar circuit but, instead of the bolometer bridge, uses a crystal rectifier and dc microammeter as the r-f voltmeter.

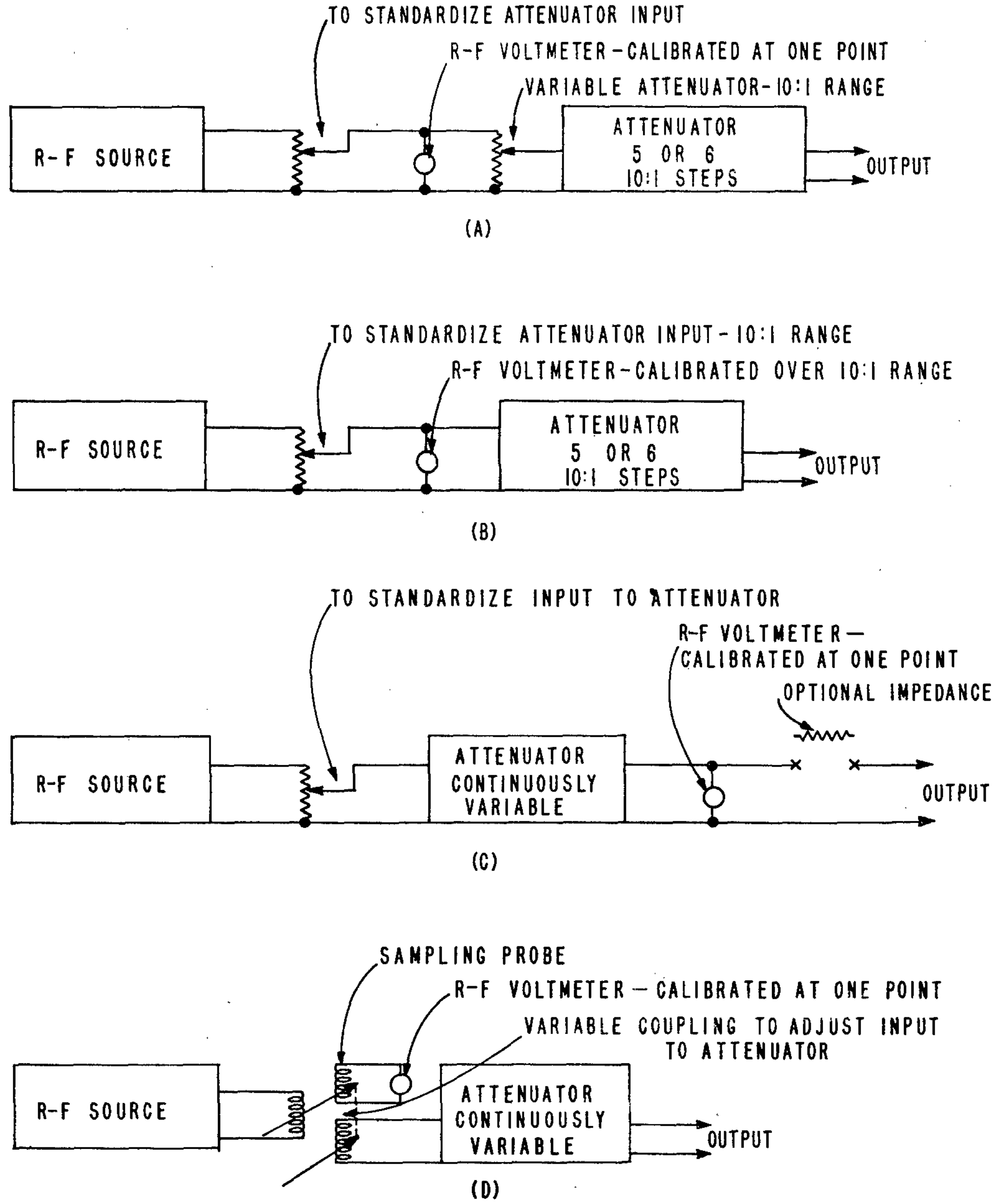


Figure 1 - Typical standard-signal generator indicator and attenuator connections

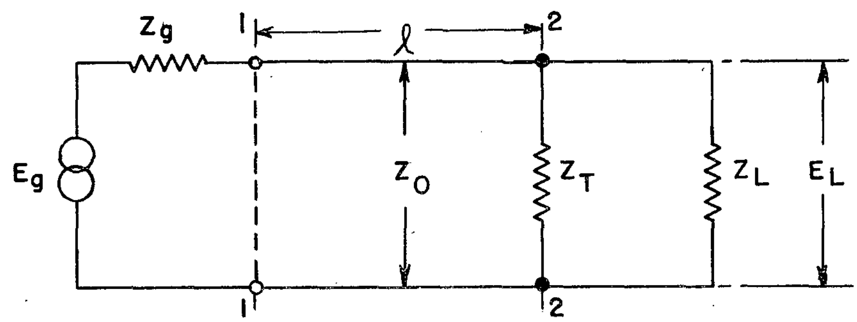
The output indicator in all modern signal generators is either a diode voltmeter or a bolometer bridge, although some older-model generators are still in service which use a triode voltmeter. All indicators are subject to changes in calibration with age, indicating that periodic recalibration is necessary. The accuracy of such instruments may also vary with frequency, although the design of the signal generator should prevent this, and calibration is necessary at a number of different frequencies within the range of the signal generator. Overload, accidental injection of r-f or dc energy into the output terminals, and other abuse may also change the calibration. Fairly frequent recalibration is obviously required, regardless of the original accuracy of the output indicator.

Attenuators in modern signal generators may be voltage divider network types, using resistive or capacitive elements, or waveguide types. The waveguide attenuator may be a "waveguide-below-cutoff" or "piston" attenuator, or it may use absorption elements in the waveguide. Once an attenuator has been accurately calibrated, changes in the calibration will occur only because of changes in electrical parts values or, in the case of waveguide attenuators, because of changes in dimensions. Such changes may occur due to aging or to abuse so that frequent recalibration is necessary to determine when such changes occur.

A very important source of error in signal-generator output calibration is signal leakage. Error owing to leakage occurs when any signal developed by the r-f source in the generator reaches the equipment under measurement without passing through the output system of the generator. Such leakage is usually due to a defect in mechanical assembly of the signal generator shielding or filtering, although some generators have leakage due to design faults. The leakage signal is usually of a low level so that the greatest error is introduced when the signal generator output is also at low level. The exact effect of leakage is impossible to predict since it depends on the relative phase and amplitude of the signal output and the leakage signal. Complete calibration must also include a study of the leakage.

Except at low frequencies and at very high frequencies, a coaxial cable is needed to conduct the signal from the output terminals of the generator to the equipment under measurement. The effect of this output cable and the impedances of both the generator and the load may introduce serious errors, both in actual use of the generator and in its calibration. An excellent analysis of the effects of the output cable and the various impedances has been published by Peterson (1). This reference is the basis of the following analysis.

The general circuit of a signal generator connected to a load impedance through a coaxial cable is



where E_g is the signal generator open circuit voltage. (The voltage appearing at terminals 1-1 when output cable is not connected.)

Z_g is the signal generator internal impedance. (The impedance which is seen when looking into generator terminals 1-1 with output cable disconnected and generator shorted.)

Z_O is the characteristic impedance of the coaxial cable,

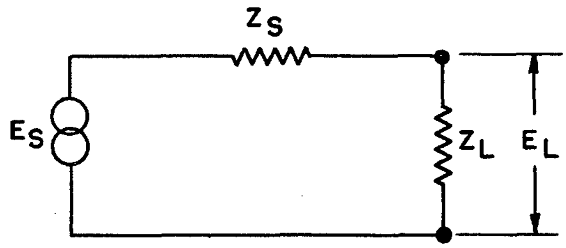
Z_T is the terminating impedance at the load end of the coaxial cable, terminals 2-2,

Z_L is the load impedance,

E_L is the voltage appearing across the load, and

l is the electrical length of the cable.

By Thevenin's theorem, the general circuit may be reduced to the equivalent circuit



where E_S is the open circuit voltage of the equivalent generator (the voltage appearing at terminals 2-2 when the load impedance is not connected), and

Z_S is the impedance of the equivalent generator (the impedance seen when looking into terminals 2-2 when the generator E_g is short-circuited).

By use of transmission-line theory the following equations may be readily developed.

$$E_S = E_g \frac{Z_O Z_T}{\left[Z_O \left(Z_g + Z_T\right) \cos \frac{2\pi l}{\lambda} + j\left(Z_g Z_L + Z_O^2\right) \sin \frac{2\pi l}{\lambda}\right]},$$

and

$$\frac{1}{Z_S} = \frac{1}{Z_O}\left(\frac{Z_O + j Z_g \tan \frac{2\pi l}{\lambda}}{Z_g + j Z_O \tan \frac{2\pi l}{\lambda}}\right) + \frac{1}{Z_L},$$

where λ is the wavelength of the radio-frequency energy being transmitted along the cable.

The electrical length, l, and the wavelength, λ, must be expressed in the same units, customarily in meters.

The voltage appearing across the load impedance is the voltage measured during calibration and is $E_L = \left(\frac{Z_L}{Z_L + Z_S}\right) E_S$.

These equations may be simplified for special cases. At low frequencies, where $l \ll \lambda$, the effect of the cable can be neglected. Then

$$E_S = E_g,$$

$$Z_S = Z_g,$$

and

$$E_L = \left(\frac{Z_L}{Z_L + Z_g}\right) E_g.$$

The available power, $P = \frac{E_g^2}{4Z_g}$.

In most low-frequency signal generators with customary load impedances,

$$Z_L >> Z_g,$$

then

$$E_L \cong E_g.$$

In many signal generators $Z_O = Z_g$ and the cable is terminated by an impedance $Z_T = Z_O$. Then

$$E_S = \frac{E_g}{2},$$

$$Z_S = \frac{Z_O}{2},$$

$$E_L = \left(\frac{Z_L}{Z_L + \frac{Z_O}{2}}\right)\frac{E_g}{2},$$

and

$$P = \frac{E_g^{\,2}}{8Z_O}.$$

If $Z_O = Z_g$ but no terminating impedance is provided $(Z_T = \infty)$, then

$$E_S = E_g,$$

$$Z_S = Z_O,$$

$$E_L = \left(\frac{Z_L}{Z_L + Z_O}\right)E_g,$$

and

$$P = \frac{E_g^{\,2}}{4Z_O}.$$

If no terminating impedance is provided and the load impedance matches the characteristic impedance of the cable, but the cable impedance does not match the generator impedance, that is, if

$$Z_L = Z_O,$$

$$Z_T = \infty,$$

and

$$Z_g \neq Z_O,$$

then

$$E_S = \left(\frac{Z_O}{Z_O + Z_g}\right) E_g,$$

and

$$Z_S = \frac{Z_O\left(Z_g + j\, Z_O \tan \frac{2\pi l}{\lambda}\right)}{\left(Z_O + Z_g\right)\left(1 + j \tan \frac{2\pi l}{\lambda}\right)}.$$

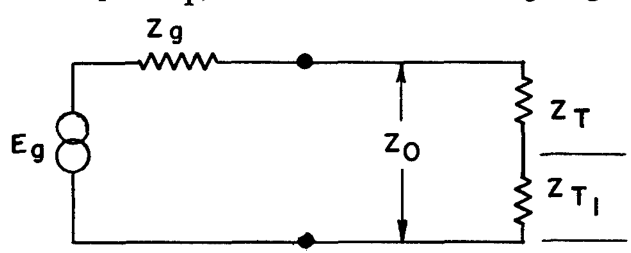
If none of the impedances match and no terminating impedance is provided, that is, if $Z_O \neq Z_g$, $Z_g \neq Z_L$, $Z_O \neq Z_L$, and $Z_T = \infty$ then

$$E_S = \frac{Z_O\, E_g}{Z_O\left(\cos \frac{2\pi l}{\lambda}\right) + j\, Z_g\left(\sin \frac{2\pi l}{\lambda}\right)},$$

and

$$Z_S = \frac{Z_O\left(Z_g + j\, Z_O \tan \frac{2\pi l}{\lambda}\right)}{Z_O + j\, Z_g \tan \frac{2\pi l}{\lambda}}.$$

Some generators provide a tap on Z_T, as shown in the following diagram:



If

$$Z_g = Z_O = Z_T,$$

and

$$Z_{T_1} << Z_T,$$

then

$$E_S = \frac{E_g}{2} \times \frac{Z_{T_1}}{Z_T},$$

and

$$Z_S \cong Z_{T_1}.$$

These equations show quite clearly the errors that may be introduced by an incorrect cable or load impedance. It is thus apparent that calibration of a signal generator should

include determination of the generator open-circuit voltage, generator internal impedance, characteristic impedance and electrical length of the coaxial output cable, and knowledge of the load impedance of the calibration instrument.

VOLTAGE MEASUREMENTS OF SINUSOIDAL SIGNALS

Since it is now evident that a measurement of the open-circuit voltage of the generator is one requirement for the calibration of a signal generator, a study of known methods for measuring r-f voltage appears desirable. An excellent study of all known methods has been made by Selby (2).

Only one method is known which is fundamental enough to be considered a primary standard and yet has sufficient sensitivity and frequency range to be used in signal-generator calibration. This is the bolometer bridge, which has been further studied by Selby (3), for use as an r-f voltage standard.

Diode voltmeters using either vacuum-tube or crystal rectifiers have also been found to have sufficient sensitivity in some cases for signal-generator calibration. Since this type of voltmeter cannot be calibrated directly against dc values, it must be considered as a secondary standard which must be calibrated by use of the bolometer bridge as the primary standard.

An ideal voltmeter consumes no energy but all practical instruments have a finite resistance and do consume energy. It is important to note that the available power from a generator having an internal impedance of 50 ohms is 0.005 micro-microwatts when the open-circuit voltage is one microvolt. The minimum energy consumption of known r-f voltmeters while indicating voltage is in the order of a microwatt which, with present generator output impedance, requires an open-circuit voltage in the order of 28 millivolts. This small amount of available power is the principal reason for difficulty in measuring the output of signal generators. Present knowledge does not indicate any method for accurate direct measurement of the signal-generator output, except at levels approaching the maximum output which the generator is capable of producing.

In spite of the small amount of available power represented by a signal of the order of a microvolt, such a signal may produce usable output from a receiver having a large amount of amplification. Obviously, the use of amplification before measurement should also be considered. This second method for signal-generator calibration of course, requires precise knowledge of the amount of amplification so that the amplifier must be calibrated by a primary standard.

It should also be possible to develop an r-f voltage of accurately known amplitude by use of special precision instruments. Utilizing a bolometer bridge, the known voltage may then be compared to that produced by the signal generator. This constitutes a third possible method for signal-generator calibration.

PRIMARY STANDARD

The sensitive element of a bolometer bridge used to measure r-f voltage is a small resistor having a large temperature coefficient. For any given temperature, the resistor has the same resistance at r-f as at dc. Heat is developed when r-f energy is dissipated in the sensitive element and the resulting rise in temperature produces a change in resistance; furthermore, a dc voltage having the same value as the effective r-f voltage applied across the resistor produces the same change in temperature. Therefore, the bolometer element may be calibrated by dc, for which accurate instruments are available.

The sensitive element is customarily connected as one leg of a Wheatstone bridge, (Figure 2a). The sensitive element may be a barretter (e.g., Wollaston wire) or may be a thermistor. A barretter is a short length of extremely small-diameter wire, often platinum wire, and has a positive temperature coefficient. A thermistor is made of a mixture of certain oxides, is usually in the form of a small bead with wire leads, has a negative temperature coefficient, and is more sensitive than the barretter. Details of both types of elements may be found in Reference (4).

The sensitivity of measurement is affected by the temperature coefficient of the sensitive element, by the choice of resistances making up the remainder of the bridge, by the galvanometer sensitivity, and by the battery voltage. The accuracy of measurement is largely determined by the accuracy of the voltmeters, V_O and V_R, and by the sensitivity of the bridge circuit which determines the precision of bridge balance. By use of a laboratory quality galvanometer to indicate bridge balance and by using precision potentiometers and a standard cell to determine the voltages, V_O and V_R, an accuracy of one percent can be attained. A detailed analysis of the circuit has been published (2 and 3). The procedure for making measurements is given, together with necessary equations.

The bolometer bridge may be used for direct measurement of signal-generator output voltage or to establish a known voltage to permit calibration by comparison. The ultimate sensitivity of the direct measurement method is approximately 20 millivolts. A signal of the same order of magnitude may be developed for comparison purposes but, since the signal must be reduced by an attenuator, it is preferable to use signals in the order of 0.1 volt as better accuracy may be obtained at this level.

The single-bolometer bridge (Figure 2a) or the double-bolometer bridge shown in Figure 2b may be used for the direct measurement method. The single-bolometer bridge requires use of radio-frequency-chokes (RFC) (Figure 2a), which limit the usable frequency range. The double-bolometer bridge, does not require r-f chokes, presents a lower resistance to the radio-frequency input and is more sensitive than the single-bolometer bridge, if all other factors are equal. The lower resistance may or may not be an advantage, depending on the requirements.

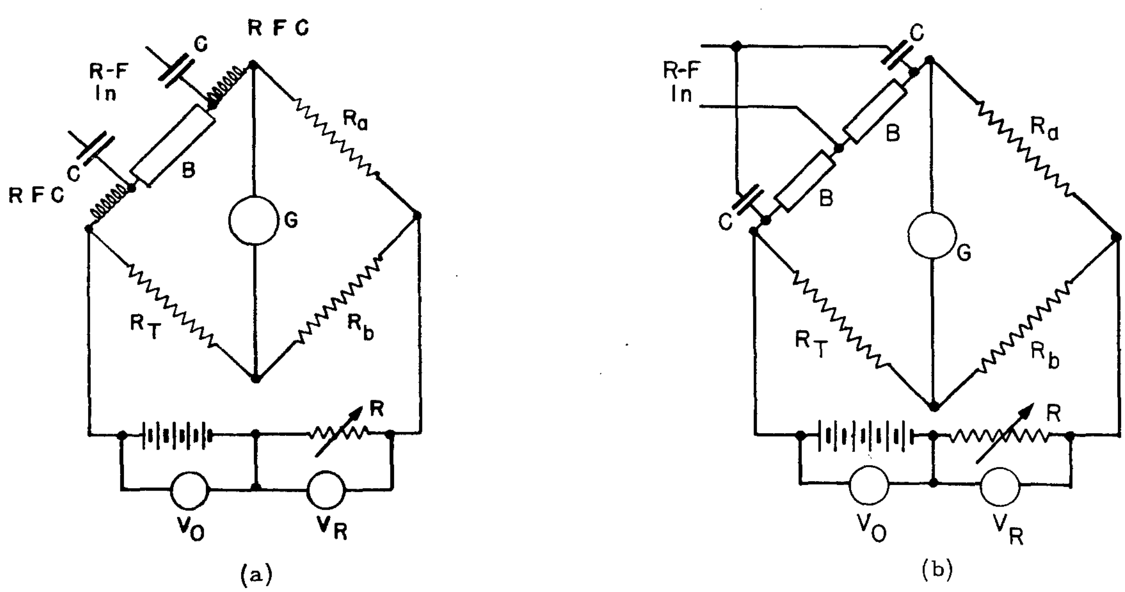


Figure 2 - Elementary circuit of (a) single-bolometer bridge and (b) double-bolometer bridge—used for measuring r-f voltage and power

The sensitive element used in signal-generator calibration is a thermistor in almost all cases. The resistance of a thermistor may be adjusted over wide limits by varying the current through it, since thermistors do not burn out without extreme overloads. The bolometer resistance may then be adjusted to match signal-generator or coaxial-cable impedances if desired. A simple method for matching impedances is possible when R_a and R_b have the same value. In this case, with a single-bolometer bridge, R_T is first adjusted to equal the signal-generator output impedance and then the bridge is balanced before applying the signal to be measured, by adjusting the resistor, R, in series with the battery. When a double-bolometer bridge is used, the two thermistors must have identical characteristics, and resistor R_T is adjusted to four times the value of the signal-generator impedance. If R_a and R_b are not equal, some calculation is required to determine the proper settings. The equation is $R_T = (B\ R_b)/R_a$, where B = desired resistance of thermistor (resistance of paralled thermistors in double-element bridge), R_b and R_a are known resistances, and R_T is required resistance.

The following procedure for employing the bolometer bridge is used not only to make direct measurement but also to establish a known voltage for comparison (Figure 2):

1. By proper adjustment of R_T as described, adjust the resistance of the sensitive element to the required value and balance bridge by adjusting R. Take readings of V_O and V_R. The voltage drop across the resistor is designated V_{R1} for this condition.

2. Apply the signal to be measured across the sensitive elements. Readjust the resistor, R, to again obtain bridge balance. Check the value at V_O, to insure that no change has occured, and read the voltage drop across the resistor, R, which is designated V_{R2}.

3. The value of the r-f signal voltage is then calculated from the following equations.

For single bolometer,

$$E = \frac{R_T}{R_T + R_a} \left[\left(V_{R_2} - V_{R_1}\right) \left(2V_O - V_{R_2} - V_{R_1}\right) \right]^{\frac{1}{2}}$$

For double bolometer,

$$E = \frac{R_T}{2(R_T + R_a)} \left[\left(V_{R_2} - V_{R_1}\right) \left(2V_O - V_{R_2} - V_{R_1}\right) \right]^{\frac{1}{2}}$$

To achieve the greatest accuracy, the effect of ambient temperature changes must be reduced. Although rapid readings may be effective, room temperature control may be required. An additional thermistor may be used for temperature compensation. The voltage, V_O, must remain absolutely constant. The resistances of the three arms of the bridge must be stable with changes in temperature and current and must be accurately known.

The bolometer bridge actually measures power which, for the calculations, is assumed to be produced by a pure sine wave. The calculated voltage is thus assumed to be the rms value of the fundamental frequency. If harmonics or other frequencies are present, the measured power will be greater than that produced by the fundamental frequency and the calculated voltage will also be in error. The presence of modulation on the signal will also introduce error. An amplitude modulated signal has a higher rms value than the unmodulated signal, though the average value is unchanged. Frequency modulation also changes the rms value of voltage.

A bolometer bridge which is used to produce a standard signal for comparison with signal-generator output is operated essentially in the same manner as when measuring the

output of a signal generator. The signal source may be another signal generator but any source having enough available power and adequate shielding may also be used. The shielding requirements are as severe as those for any standard-signal generator.

In addition to the bolometer bridge and r-f source, an accurately calibrated attenuator is also necessary. The standard-signal voltage developed across the bolometer is normally at a level of the order of 0.1 volt. The calibrated attenuator then reduces this high-level signal to lower values which may be as low as 0.1 microvolt. The calibrated range of the attenuator should be at least 100 db and preferably 120 db.

Before discussing the attenuator requirements in detail, the general method will be described. In addition to the r-f source, the bolometer bridge and the calibrated attenuator, an r-f indicator capable of indicating relative voltage levels and sensitive enough to detect a signal of the minimum amplitude to be measured is also required. An ordinary receiver of suitable frequency range and sensitivity with some sort of meter to indicate the rectified dc output of the second detector is satisfactory for this purpose. An r-f field-strength meter may also be used. The indicator may be a high-resistance, dc voltmeter connected across the second detector load resistance. The receiver should use manual gain control as automatic gain control compresses the scale of the indicator and reduces accuracy of comparative readings. Instead of manual gain control, an attenuator having a wide range of attenuation may be connected in the receiver input circuit, and the receiver gain may be fixed.

The block diagram of the circuit for calibrating a signal generator by comparison with primary standard is shown in Figure 3. The procedure is, first, to establish a known voltage across the bolometer elements by adjusting and measuring the voltage from the r-f source. The signal is then attenuated in some desired ratio by the calibrated attenuator. The receiver gain control (or input attenuator) is adjusted to obtain some arbitrarily selected output indication. The switch is then shifted to connect the signal generator to the receiver and the signal generator output controls are set to obtain the same receiver output indication. The standard signal and the signal from the generator are then equal, provided the equivalent source impedance of the generator and standard signal, as defined earlier, are identical. The signal generator and the standard-signal source are, of course, adjusted to produce identical frequencies. True, open-circuit voltage must be calculated by correcting for the effects of the source, cable,and load impedances.

Another variation of this method does not have the attenuator connected to the bolometer element. In this procedure, the bolometer bridge is used to measure directly the output of the signal generator at a high level, near the maximum output. The bridge is then disconnected and the calibrated attenuator input is connected to the signal generator while the attenuator output is connected to a receiver. The receiver gain is adjusted to near maximum to yield an easily readable output indication when the calibrated attenuator is set to produce a large amount of attenuation. The signal-generator output attenuator is then adjusted to introduce a small amount of attenuation and the calibrated attenuator is readjusted to produce the original output indication from the receiver. The change in the calibrated attenuator ratio indicates the change in the signal-generator attenuator output. This procedure is followed over the usable range of the calibrated attenuator. If the fixed insertion loss of the calibration attenuator is known, the true output voltage of the signal generator may be calculated. If the fixed attenuation is not known, the information obtained may be used to plot a curve of actual attenuation of the signal-generator attenuator versus indicated attenuation. Changes in the slope of the curve, which indicate attenuator inaccuracy, may be easily detected. The proper slope of the signal-generator output attenuator curve may sometimes be calculated and compared with the measured value to obtain an indication of the degree of inaccuracy.

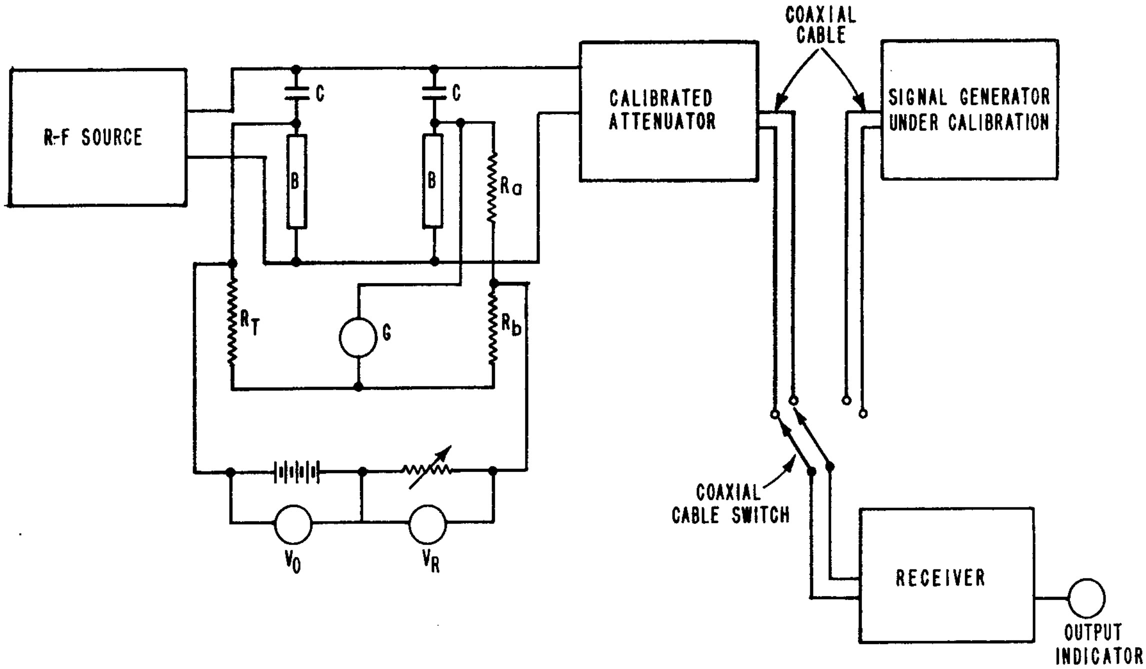


Figure 3 - Block diagram of circuit for calibrating signal generator by comparison with primary standard

CALIBRATED ATTENUATOR

If the method is to be considered as a primary standard, the calibrated attenuator must be as accurate as the bolometer bridge and must also be capable of calibration in fundamental terms, such as measurement of the dimensions or dc values of component parts. Resistive type attenuators meet this requirement at frequencies below the vhf range and some late models are claimed to be useful to several thousand megacycles. It is difficult to establish the maximum usable frequency for such attenuators, however, as errors are usually due to small stray reactances which are difficult to measure.

The waveguide-below-cutoff or piston attenuator can be calibrated from its dimensions alone and is suitable for use as a standard attenuator over a wide frequency range. This type of attenuator consists of a short length of waveguide, usually circular, which has internal dimensions much smaller than that required to transmit energy at the frequency of the signal to be evaluated. The attenuation per unit length is a function of the size of the waveguide, the spacing between the coupling devices in the guide, and the mode of propagation, as well as a function of the ratio of the wavelength of the signal to the wavelength of the frequency at which the guide begins to transmit energy. Numerous references may be found giving details of construction (4 and 5).

The most useful transmission mode for the application described appears to be the TE_{11} mode in circular waveguide. This mode has the minimum attenuation per unit length of all modes. The attenuation is calculated from:

$$a = 16 \sqrt{1 - \frac{\lambda_o^2}{\lambda^2}} \left(\frac{s}{r}\right)$$

where a = attenuation, db,
λ_o = cutoff wavelength = 3.46 r,
r = radius of waveguide, in centimeters,
s = spacing between elements, in centimeters, and
λ = wavelength of signal.

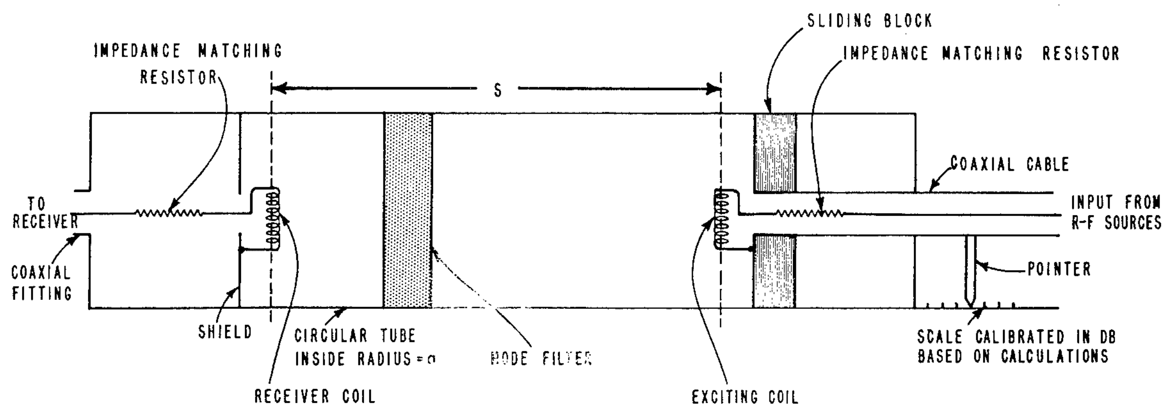


Figure 4 - Typical standard calibrated attenuator

A sketch of an attenuator of this general type is shown in Figure 4. The attenuation is usually calculated from $a = 16\ s/r$ and a correction chart based on $a = 16\sqrt{1-(\lambda_o^2/\lambda^2)}(s/r)$ is used to correct the scale calibration at the frequency in use. The correction is negligible if $\lambda_o/\lambda \leqq 0.134$. This type of attenuator follows very definite laws after the ratio s/r exceeds a minimum value of about two. The calibration is nonlinear for smaller spacing and cannot be easily calculated. The unknown attenuation also varies with frequency and must be determined by measurement at each frequency.

The method for determining the fixed insertion loss of an attenuator may be any established method for measuring attenuation, such as comparison with another attenuator. One such method requires another calibrated attenuator which may also have an unknown fixed insertion loss, a source of r-f energy, and a receiver with necessary coaxial cable and shielding. The calibrated attenuator is connected between the r-f source and the receiver and is set to introduce as large attenuation as possible while permitting a readable indication on the receiver output indicator. The attenuator to be measured is set for zero attenuation on its calibrated scale and added in series with the calibrated attenuator. The calibrated attenuator setting is then reduced to duplicate the receiver output indication obtained in the first measurement. The change in the two attenuator indications is the value of fixed insertion loss introduced by the second attenuator. It is necessary, of course, that the impedances of the r-f source, input and output of the attenuators, and input of the receiver all be equal.

Another factor which can produce inaccuracy is the presence of undesired modes of transmission in the waveguide. The attenuation per unit length of guide differs for each mode and is greater for all other modes than the TE_{11}, but error may be introduced at low attenuation settings. Of the numerous mode filters which may be inserted, one of the simplest (4) consists of a metal ring of a diameter that will just slip into the attenuator, with a width of about 1/8 inch. Fifteen copper strips of the same width are spaced equally across the ring (Figure 5) which is fastened in the waveguide between the two coils.

The accuracy of such an attenuator is largely determined by the precision of construction and by the exactness of measurement of the fixed attenuation. An accuracy of 0.2 db or 5 percent should be obtained.

SECONDARY STANDARDS

An attenuator which is required to operate on only one frequency can be made more accurate than one which is to cover a wide range of frequencies. It is also difficult to design a piston attenuator of the required accuracy for frequencies greater than about 1000 Mc. For those reasons, at least two laboratories (4 and 6) have developed a method which operates the standard attenuator on a fixed, comparatively low frequency. A bolometer bridge may be used in this method also to further improve the accuracy. The over-all method cannot be calibrated in fundamental units and has enough possible sources of error to prevent its classification as a primary standard. The method of operation (Figure 6) will be described before the sources of error are analyzed.

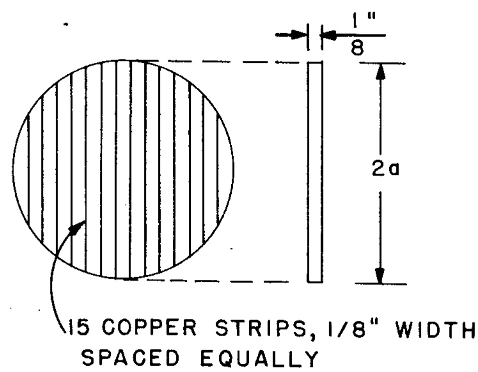


Figure 5 - One type of mode filter for use in calibrated attenuator

The procedure for using this method is:

1. With the signal generator disconnected and the high-frequency oscillator connected to the linear converter by means of switch SW_1, a signal of known magnitude, as determined by h-f voltmeter No. 1, and of the same frequency as the signal generator, is injected into the linear converter from the oscillator.

2. The local oscillator is adjusted to the proper frequency relative to the h-f oscillator necessary to develop a beat frequency which is equal to the i-f frequency. The amplitude of the local oscillator signal is adjusted so that it is several times as great as the h-f oscillator signal.

3. Switch SW_2 is set to connect the output of the linear converter to the i-f amplifier. The gain of the i-f amplifier is adjusted to obtain some arbitrary indication of the output meter.

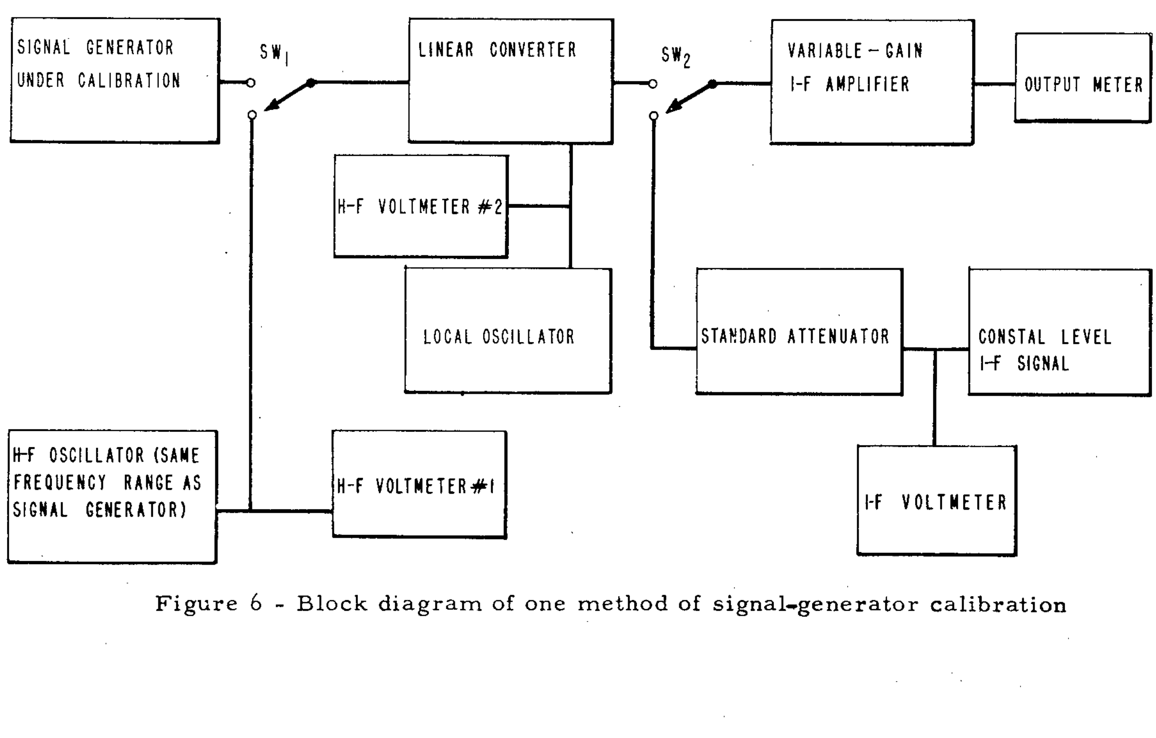


Figure 6 - Block diagram of one method of signal-generator calibration

4. Switch SW_2 is then shifted to connect the output of the standard attenuator to the i-f amplifier. The level of the constant output i-f oscillator is adjusted by the standard attenuator until the arbitrary reading of the output meter obtained in step 3 is repeated. This attenuator setting is noted as the reference point.

5. Switch SW_2 is shifted to again connect the linear converter to the i-f amplifier and switch SW_1 is set to connect the signal generator to the linear converter input. The gain of the i-f amplifier is then adjusted to obtain an arbitrary output indication with the desired input from the signal generator.

6. Switch SW_2 is again shifted to connect the standard attenuator to the i-f amplifier and the attenuator is adjusted to duplicate the output indication obtained in step 5. The difference in the attenuator setting for this reading and for that obtained in step 4 establishes the ratio between the voltage of the h-f oscillator and the signal generator.

7. At each frequency, the procedure of steps five and six are repeated at enough different, signal-generator output levels to permit a calibration of a large part of the range of the signal-generator output. When the frequency is changed, the procedure of steps 1 through 4 must again be repeated to determine the reference point of the attenuator.

It is apparent that errors may be introduced into this method from a number of sources. The whole method is based on the assumption that the converter is linear, that is, that the ratio of the input voltage from the signal generator or h-f oscillator to the i-f output voltage is constant, regardless of the level or frequency of the input signal. It is known that this relationship is approximately true when the amplitude of the local oscillator output is much greater than the amplitude of the signal input voltage. There seems to be no proof that this relationship is true within the required limits of accuracy over the wide range of signal levels which a signal generator produces.

The output voltages of the h-f oscillator, the local oscillator, and the i-f oscillator must remain constant throughout any calibration using this method. Accurate voltmeters must be attached to the output of each oscillator to measure the level and insure that it is constant. The voltmeter connected to the h-f oscillator must be accurately calibrated as the voltage measured at this point is the standard voltage for this method. The local oscillator and i-f oscillator voltmeters do not require exact calibration but must indicate accurately any change in level of the respective signals and give an approximate indication of the voltage. For best accuracy all voltmeters should be bolometer bridges, but the use of diode rectifiers for the local oscillator and i-f oscillator output indicators will probably be satisfactory.

The i-f amplifier must provide enough gain to amplify the lowest level signal to be measured to a level high enough to be indicated. This requires a maximum amplification of approximately 1,000,000 times since the minimum signal to be measured will produce an output from the linear converter in the order of 0.1 to 1 microvolt. The amplifier gain must be adjustable so that the maximum signal to be measured, in the order of 1 volt, will not overload the amplifier and indicator. An i-f amplifier frequency of about one megacycle for low-frequency, signal-generator calibration, and about 20 to 30 megacycles for higher-frequency generators appears to be satisfactory. The amplifier gain control requires more than merely varying the grid bias of the tubes, since this may not yield a wide enough range of control. Usually, attenuator networks or variable load resistors are provided between amplifier stages.

The standard attenuator for the one megacycle amplifier may be a resistive voltage divider or "ladder" attenuator since resistance components can be be made quite accurate at this frequency and a dc calibration is satisfactory. For the 20 or 30 megacycle amplifier, the attenuator is usually a piston or waveguide-below-cutoff type, using inductive coupling elements. The linear converter is a diode vacuum tube for low frequency and a

crystal for higher frequencies. For the calibration frequency, the tuned circuits associated with the converter are appropriate. Lumped-constant circuits are usable for frequencies below 100 Mc and transmission line circuits are useful for frequencies between 100 Mc and 500 Mc, while resonant cavity circuits are necessary for higher frequencies. In all cases impedance matching is the important consideration. The input impedance looking into the linear converter must be the desired value, as determined by considering the signal-generator output impedance and coaxial cable impedance and length.

The i-f oscillator must have both a stable frequency and a stable output. Because of the fixed frequency of operation, this is not extremely difficult to obtain, particularly if crystal control is used. The maximum accuracy of this method (Figure 6) may approach that of the bolometer bridge used to measure the h-f oscillator. Practically, because the total error may be as great as the sum of the individual voltmeter and attenuator errors, an accuracy better than 5 percent should not be expected. Deviations of the linear converter may further decrease this accuracy.

DIRECT MEASUREMENT BY R-F VOLTMETER

All modern radio-frequency voltmeters, except the limited-frequency-range, feedback amplifier type, use a diode as a rectifier to convert the radio-frequency to direct current which charges a condenser. The rectifier may be a vacuum tube diode or a germanium or silicon crystal. The dc voltmeter which measures the voltage produced by the charge may be a moving-coil meter, but better sensitivity and a higher resistance are obtained by using a vacuum tube voltmeter.

The variation between individual rectifiers and the uncertainity of knowledge about the response of such rectifiers make it necessary to individually calibrate each instrument. Vacuum tube diodes are more stable in their characteristics than crystals but crystals are usually more sensitive and are often usable at higher frequencies than vacuum tubes.

The maximum sensitivity of commercial radio-frequency voltmeters using a vacuum tube rectifier is in the order of 0.1 volt and the accuracy at this low value is poor. At least one voltmeter using a crystal recitifer is available which is calibrated for voltages less than 10 millivolts. The basic circuit of such an instrument is shown in Figure 7.

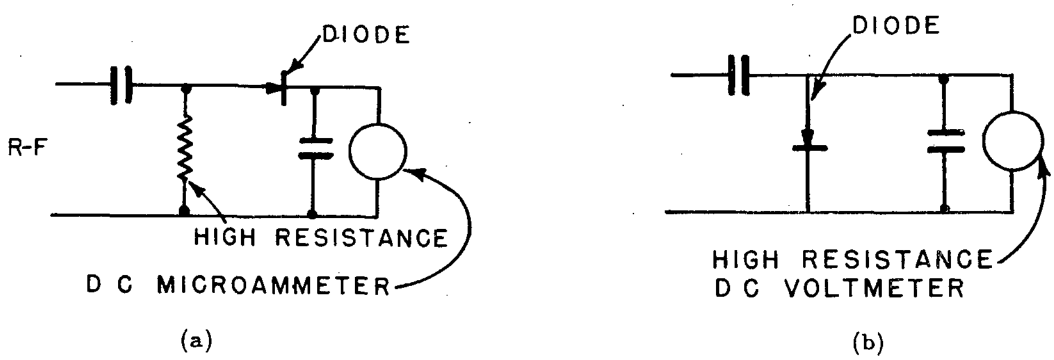


Figure 7 - Basic circuits of rectifier-type r-f voltmeter

In general, if the resistance of the voltmeter shunted across the condenser is very large, the rectifier charges a condenser to a dc voltage which approaches the peak value of the r-f voltage. The instrument is basically a peak reading voltmeter but the calibration is usually in terms of the rms value of the voltage.

The response of such instruments is linear (that is, dc voltage is directly proportional to r-f voltage) at r-f voltage levels greater than about 0.25 volts in the case of crystals, or about one volt in the case of vacuum tubes. The response to lower voltage is more nearly a square-law response, that is, the dc voltage is proportional approximately to the square of the r-f voltage. This type of response limits the minimum r-f voltage that can be measured to about 2500 microvolts, since crystals apparently cease to rectify at a voltage of this level. For example, a 1N 34 crystal (germanium) produces an output of approximately one millivolt dc with an r-f input of 10 millivolts, an r-f input of three millivolts produces about 0.1 millivolt dc, and an input of slightly over two millivolts r-f shows no measurable dc output. Vacuum tubes apparently become almost useless at about 0.1 volt. There thus appears to be little chance of increasing the sensitivity of the rectifier-type voltmeter.

Since the maximum sensitivity is about 0.1 volt, a vacuum tube rectifier voltmeter seems to be of slight value in calibrating signal generators. Such an instrument may be used in calibrating the r-f indicator or monitor of signal generators having an output of one volt and for checking the attenuator of such a generator over a 10:1 range of attenuation.

Because of its greater sensitivity, a crystal rectifier meter may be used to check the output indicator of all signal generators, but it must be calibrated against a primary standard to obtain the desired degree of accuracy. A less accurate calibration may be made on 60-cycle ac by use of a precision ac voltmeter and a voltage divider, provided a large-capacity condenser is temporarily connected in the rectifier circuit. This calibration assumes that the response of the crystal at r-f is the same as at low-frequency ac. The accuracy of a signal-generator calibration with such a voltmeter will probably be better than 10 percent. A more accurate crystal voltmeter calibration may be made at radio frequencies by use of a bolometer bridge.

Another type of vacuum tube voltmeter, which has some value for calibrating a signal generator, is the feedback amplifier type. This type of instrument uses a high-gain, wide-band amplifier which incorporates a large amount of negative or degenerative feedback. The feedback stabilizes the gain characteristics of the amplifier so that changes in tube characteristics or in tube voltages have negligible effect on the over-all gain. The output of the amplifier is then rectified and actuates a dc microammeter. The most widely known commercial instrument of this type is the Ballantine Model 300 Electronic Voltmeter which has a useful frequency response extending from 10 cycles to 150 kilocycles. The sensitivity is such that the first calibrated point on the scale is one millivolt and the maximum indication is 100 volts. The calibration of this instrument is logarithmic so that the accuracy is the same at any point of the scale. Since the scale calibration is in terms of rms value of a sinusoidal voltage but the indications are proportional to the average value, the presence of harmonics in the measured voltage may introduce inaccuracies. The specified accuracy is within 3 percent on sinusoidal voltages and may be better than this if calibrated against a bolometer bridge or some other accurate standard.

The Ballantine Model 300 Voltmeter may be used to measure directly the output voltage of signal generators having a frequency range extending below 150 kc. The output monitor calibration can be checked directly and several steps of the attenuator may also be measured. Also available is a decade amplifier, Ballantine Model 220, which provides fixed gains of 10 or 100 times at frequencies between 10 cycles and 100 kc. By connecting this decade amplifier between the signal generator and the Model 300 Voltmeter, the calibration of the attenuator may be extended to approximately 50 microvolts. The theoretical limit of 10 microvolts cannot be attained because of noise.

This type voltmeter is now available from other manufacturers. In addition, there is available another Ballantine Model Voltmeter, which operates on the same principle but has a usable frequency response extending to 5 Mc. However, a decade amplifier is not available for this higher frequency range so the maximum sensitivity is one millivolt. The latter voltmeter may be used in the same way as the Model 300 Voltmeter but the accuracy is 5 percent unless it is specially calibrated by a bolometer bridge.

FIELD-STRENGTH METERS

It is apparent that a signal of one microvolt may be amplified by a tuned r-f amplifier to a level at which reasonable dc voltage can be obtained by rectification, since this is substantially what occurs in radio receivers. The major difficulty, which limits use of this method in signal-generator calibration, is that of obtaining a known and stable amount of amplification at each frequency before rectification.

A class of instruments known as field-strength meters are intended to measure r-f energy at levels in the order of a microvolt. Designers of these instruments have not only attempted to stabilize the amplification so that wide variations do not occur, but also included internal calibration methods so that compensation can be introduced for the variations which remain. These instruments offer possibilities for use as radio-frequency voltmeters in signal-generator calibration. The accuracy of such instruments, which is in the order of 10 percent, is limited by remaining instability, difficulty in reading the calibrated scale, and variations with frequency. Calibration against a primary standard will reduce the variation with frequency but will not affect the principal errors.

An additional difficulty is that most field-strength meters have a balanced input circuit while almost all signal generators have an unbalanced output. This requires use of additional components to convert from balanced to unbalanced circuits. Such components also change voltage levels and must be individually calibrated to determine the change.

Field-strength meters thus appear to have little value for direct measurement although they may be used as the indicator for calibration by comparison methods.

COMPARISON WITH OTHER SIGNAL GENERATORS

Most standard-signal generators have adequate stability so that an accurately calibrated model may be used to furnish a secondary standard voltage to which other generators may be compared. Some models, such as the Hewlett-Packard Model 608A or the Measurements Model 80, include a bolometer bridge and a piston attenuator but these components are not accurate enough to be considered as primary standards.

A group of signal generators may be selected and calibrated for use as secondary standards. Such instruments should be set aside to be used only for signal-generator calibration. These instruments, if periodically checked against the primary standard, may be used for all signal-generator recalibration. It is, of course, necessary to provide radio receivers having an adequate frequency range, enough sensitivity, and suitable output indicators to be used with the signal generator for comparing r-f voltages.

If a calibration in absolute terms is not necessary, a group of signal generators may be adjusted by comparison so that the output voltages agree. These may then be used to calibrate other instruments so that all measurements will agree relatively.

SECOND-HARMONIC SIGNAL GENERATOR

A device called a second-harmonic signal generator, which produces an r-f voltage whose amplitude is measured by a dc meter, is capable of a high degree of accuracy over a limited frequency range provided a number of conditions are complied with. The device (Figure 8) is usable in developing frequencies in the order 30 Mc or less (7 and 8).

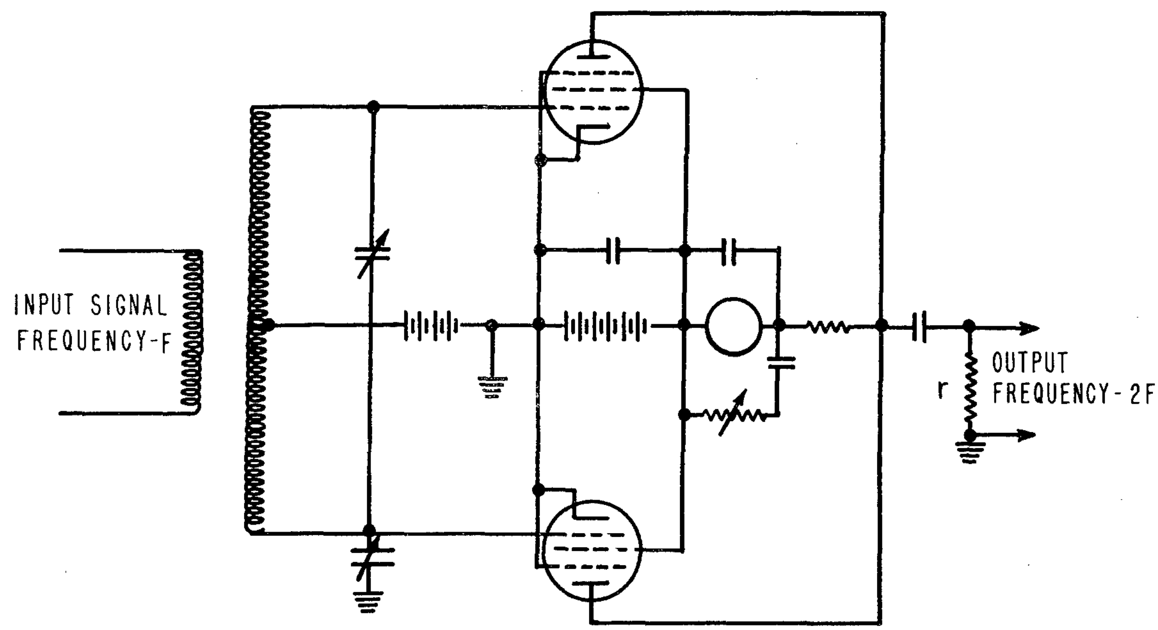


Figure 8 - Typical circuit of second-harmonic signal generator

The tubes are operated as balanced square-law detectors. The no-signal plate current is balanced out of the meter by the shunt battery and resistor. It can be shown that the plate current of a balanced square-law detector contains, among other components, a second harmonic of the input signal and a rectified dc current. The peak amplitude of the second-harmonic current may be shown to be exactly equal to the dc current. The second-harmonic current flows through the resistor, R, and produces a known r-f voltage having a peak value $E = IR$, where I is the dc current and R is the r-f resistance of the resistor, r. If R is one ohm and the dc meter has a sensitivity of a few microamperes, the voltage may be a few microvolts.

Design requirements are:

1. The plate resistance of the tubes must be much greater than the circuit resistance to the second-harmonic and dc components.

2. The tubes must follow the square-law response quite accurately.

3. The circuit must be well balanced.

4. The no-signal plate current must be balanced out accurately and stably.

5. The input signal must not be modulated and must have a small harmonic content.

6. The input and output signal frequencies must not exceed the usable frequency range of the tubes.

If properly designed, the second-harmonic generator voltage may be used to calibrate signal generators, using the comparison method. The accuracy will be a few percent, over a limited range of a few hundred microvolts, at frequencies below the vhf range.

MISCELLANEOUS METHODS OF CALIBRATION

Many other methods of signal-generator calibration have been used at various times. Each method has some uses but all have some disadvantage or limitation which makes its general use inadvisable. A brief description of four practicable methods follows.

Comparison Method

A small r-f voltage has been developed for calibration by comparison by passing a known r-f current, measured by an r-f microammeter (generally a thermocouple meter), through a known, low-value resistor. The minimum voltage that can be developed by this method is limited because the maximum sensitivity of an r-f microammeter is in the order of 500 microamps and the minimum practical value of the resistor is in the order of 0.1 ohm. Since the accuracy of an r-f microammeter is in the order of 5 percent, and accurate measurement of low-value resistances at r-f is also difficult, the over-all accuracy is probably 10 percent. The resistance of a microammeter of this sensitivity is in the order of 2000 ohms so that the r-f source required to produce the current flow of 500 microamperes must be about 1 volt. This source must be shielded from an output voltage of the order of microvolts, which is hard to accomplish. This method is very difficult and has comparatively poor accuracy.

Voltage Divider Method

Radio-frequency voltages of microvolt-level have been developed by various types of voltage divider arrangements, one of which utilizes a transmission line shorted at one end and tapped at various points. This involves difficulties in measuring current of low values, in shielding output from input, and in determining characteristics of the transmission line. A variation of this method uses a coupling loop to pick up the desired voltage from the transmission line but this is subject to the same errors as the tapped line plus other errors in calculating the coupling.

Linear Output Method

One method for checking attenuator ratios, which is comparatively inaccurate but has some practical value, is based on the assumption that the output of a radio receiver is fairly linear over a 10:1 range of r-f input voltages. This is approximately true of the voltage across the second detector load resistance in most superheterodyne receivers, provided the r-f input to the second-detector is in excess of one volt, and provided automatic gain control is not included to control the gain of the r-f amplifier ahead of the detector. A gain control using variable grid bias or similar means is necessary unless an r-f attenuator is included in the receiver input circuit or between the mixer and r-f stages.

In using this method the signal-generator attenuator is set for a low output and the receiver gain controls are adjusted to produce a receiver output indication of near the maximum obtainable value. The receiver gain control is then adjusted to reduce the receiver output to one-tenth the first value. The signal-generator output attenuator is then readjusted

to produce ten times the first output and the receiver output indication should return to the first value. Intermediate points in the 10:1 range of the attenuator are checked by assuming the ratio of the dc voltages correspond to the ratio of r-f voltage.

This method is useful for checking large errors in the attenuator but the accuracy is probably less than that required for an accurate calibration. The range of voltage which can be measured by this method is restricted to values between a minimum determined by the maximum sensitivity of the receiver, and a maximum set by the point of overload of the receiver amplifier. Linearity of the receiver gain over a 10:1 range of input voltage at low levels is also doubtful.

Modulated Signal Method

In order to permit further amplification after rectification of the signal, some methods have used a modulated signal from the signal generator under calibration. For example, in the linear output method, the indicator may be an a-f voltmeter connected to the second detector by one or two stages of a-f amplification if the input signal is amplitude-modulated at an audio-frequency. This method is of questionable accuracy because linearity of a-f output from a second-detector is more difficult to prove than linearity of dc output. Variations in the degree of modulation will also introduce error, as will carrier shift, harmonics of the modulating voltage and distortion introduced by the detector.

Another method requiring a modulated signal uses a bolometer as a detector. The direct-current through the bolometer is adjusted so that the ac voltage developed across the bolometer is proportional to the r-f power input. An a-f amplifier, usually tuned to the modulation frequency of the signal generator, is connected to the bolometer and a Ballantine Voltmeter is connected to the amplifier output. A high-level signal from the signal generator is applied to the bolometer and the voltmeter reading is noted. The signal is then reduced in steps by the signal-generator attenuator and the change in voltmeter reading is noted. Preferably, the attenuator and voltmeter readings should be expressed in decibels with reference to the first reading. Since the bolometer has a square-law response, a change of one db in signal-generator output produces a change of two db in the voltmeter reading. This method is of value primarily for determining any discontinuity or change in slope of the attenuator curve and the accuracy is rather low. The minimum signal which can be measured is of the order of 10,000 microvolts and the range of measurement is about 20 db. This method may also be used in measuring the output of pulsed signal generators. A crystal detector may be substituted for the bolometer but each crystal requires an individual calibration as the response law is not definite.

It is obvious that all methods requiring signal modulation are subject to so many limitations of range and accuracy that none are suitable for accurate calibration.

MEASUREMENT OF PULSE-MODULATED SIGNALS

All methods of signal-generator calibration described thus far except one have been applicable only to generators producing a continuous wave output, which may be amplitude or frequency modulated. Another class of signal generator produces a carrier frequency which is periodically turned off and on or varied in amplitude in discrete steps, a procedure known as pulse-modulation. The carrier is generally turned off for a large portion of the time and turned on by the pulse for a very short interval of time which permits individual pulses to have high power but retains a low average power.

The quantity of primary interest in a signal generator using such modulation is generally the peak value of the available r-f power. Since available power from a signal generator is also the power dissipated in a load which matches the impedance of the signal

generator, a peak voltage measurement across the desired impedance to which the signal generator is connected yields the desired result. If the pulse recurrence frequency, pulse shape and length are known, the peak power may also be calculated from the average power. However, the average power is usually so small that it is very difficult to measure.

Average power, if high enough, may be measured directly by a bolometer bridge, as the sensitive element in such a bridge, although calibrated in voltage, actually measures average power. The maximum sensitivity of such a bridge is in the order of a few microwatts.

At least one method (Figure 9) has been developed to permit direct measurement of the peak power by comparing it with continuous wave power which may be more easily measured. The pulsed r-f signal and the cw signal are adjusted to the same frequency and mixed in a receiver. The amplitude of the cw signal is adjusted by means of the attenuator, with a fixed amplitude pulsed signal, until the figure (Figure 10) is obtained on the oscilloscope. When this figure is obtained, the peak voltage of the pulse is twice that of the cw signal or the power of the pulse is four times that of the cw signal. The power of the cw signal is then measured by use of the voltmeter which is usually a bolometer bridge. This procedure is repeated over as wide a range of output power as possible but is limited in range by the sensitivity of the bolometer bridge.

Another method of calibration often used is based on the assumption that the peak amplitude of the pulsed signal is the same as the peak amplitude of the signal when the generator is producing a continuous wave. The signal generator is then calibrated by any applicable method while generating cw signals. Some pulsed signal generators, however, cannot produce a cw signal. Since the validity of the assumption is also doubtful, direct measurement of the pulsed signal is preferred.

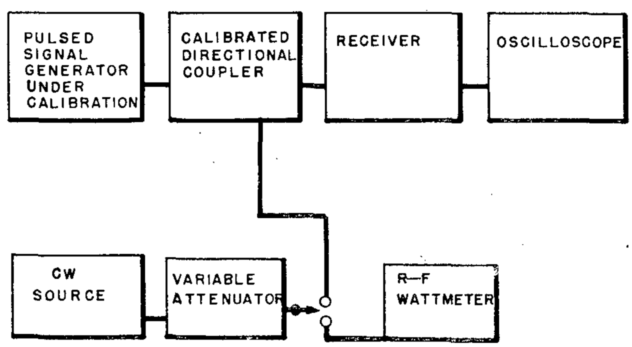


Figure 9 - Block diagram of method for calibrating pulsed signal generators

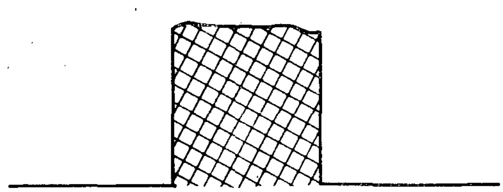


Figure 10 - Example of proper pulse shape in calibration of pulsed signal generators

MEASUREMENT OF SIGNAL LEAKAGE

In general, signal leakage may occur in two degrees of magnitude. Leakage of a signal of large magnitude is almost always caused by some mechanical defect which is usually evident on close inspection. For example, failure to reinstall a shield in assembly of a signal generator after repairs may result in high leakage signals. Measurement of the magnitude of such leakage is unnecessary as all that is required is some device for indicating that such leakage is occurring. A small probe, which may be a small loop or a short rod, connected by a short length of coaxial cable to a receiver of suitable frequency range, is satisfactory for this. At frequencies above vhf, a horn antenna is the most suitable pickup device. Some sort of output indicator should be included in the receiver. The probe is placed close to the signal generator and moved around it while the receiver output indicator is noted. It is usually necessary to shield the signal-generator output connections for this measurement, but it may be adequate to reduce the signal generator output to a minimum by use of the attenuator. Substantial indication of the presence of an r-f field indicates that leakage is occurring. The exact point of leakage can usually be determined by the probe. The frequency on which this check is made is not critical, since leakage due to a mechanical defect will occur on any frequency developed by the signal generator. This check permits serious defects to be located and repaired.

All standard signal generators are designed so that, when properly assembled, leakage will be of a low magnitude. Leakage of low magnitude introduces serious errors only at a low output level from the generator, for example, a leakage signal of 10 microvolts can introduce very little error when the signal generator output is 1000 microvolts. However, the same magnitude leakage signal when the generator output is also 10 microvolts may cause the resulting signal applied to the load to be any value between zero and 20 microvolts, depending on the relative phase of the two signals. A leakage signal of 10 microvolts may introduce a 10 percent change in a generator output of 100 microvolts.

The leakage may occur in either of two ways, or in combination, that is, through defects in the shielding or as conducted energy leaking through power-line or other line filters. The leakage signal may be applied to the load by conduction or by establishing r-f fields which couple to the load.

It is difficult to accurately measure leakage of low magnitude. With a few exceptions signal-generator manufacturers do not attempt to specify any exact limits. Generally, the specifications merely state that leakage cannot be detected with a high-sensitivity receiver, without any indication of a method of measurement.

The same method described for detecting high-level leakage may be used for low-level signals also, but the sensitivity is so limited that leakage signals of sufficient intensity to introduce appreciable error may not be detected. A small loop probe may be calibrated (9) so that the approximate field strength may be indicated. Such calibration for this purpose is of little value, however, since any leakage detected by this method is strong enough to introduce significant error and its exact value is unimportant. It seems more worth while to merely determine if leakage is occurring. If detected, inspection of the mechanical assembly may reveal the source of leakage which can be eliminated by the appropriate measure, such as tightening screws, soldering broken shielding connections, adding additional shielding, or similar methods.

The presence of leakage signals may be indicated during the calibration process by several check methods. A certain indication that leakage is occurring may be obtained when a signal generator is connected to a sensitive receiver for calibration by comparison. The attenuator in the signal generator is gradually adjusted to introduce an increasing amount of attenuation, beginning with an output level of the order of one hundred microvolts. The output indicator of the receiver should indicate a continuous reduction corresponding to the increase in attenuation. If leakage is present, the receiver output indicator will show a

reduction to some minimum value and then will show no further decrease, or may even indicate some increase in output as the generator attenuation is further increased. The receiver must have sufficient sensitivity to indicate satisfactorily a signal level near the minimum produced by the generator. A check must also be made to determine that the receiver output indication is not caused by a signal from another source. This is done by removing power from the signal generator, while the receiver is indicating the leakage, and noting that the receiver indication decreases to the value obtained with no signal input. This check also determines whether the receiver indication is caused by noise, which may be developed in the receiver or in the signal-generator output impedance, rather than by leakage.

Another indication of leakage is a change in the receiver output indication when persons in the vicinity of the generator and receiver change positions relative to the equipment, while a low magnitude signal is applied from the generator. A change in indication when the generator or receiver is touched by the operator is also an indication of leakage.

Since both the relative phase and amplitude of the leakage and desired signals affect the resultant voltage, and both the phase and amplitude may change with frequency, these checks should be made at several calibration frequencies.

It should also be noted that leakage will almost always be indicated at frequencies above 10 Mc from signal generators which have binding post type output terminals. This is caused by radiation of energy from the binding posts and by circulating currents which appear on the outside of the output cable and signal-generator shield. An accurate calibration of such a generator at frequencies where this phenomena occurs is possible only by adding adequate shielding over the binding posts and is not always possible even with added shielding.

GENERAL PROCEDURE FOR SIGNAL-GENERATOR CALIBRATION

A general procedure for signal-generator calibration is as follows:

1. Study the signal generator to be calibrated and determine the essential design characteristics and other information required for calibration, including:

   a. The available frequency range,
   b. Range of calibrated output voltage or power,
   c. The terms of calibration, that is, determine if voltage (or power) indicated by monitor and attenuator is the open-circuit voltage, voltage developed across a specified load impedance, available power or other value, and
   d. Signal-generator output impedance.

2. Make a thorough visual inspection to determine that the generator is in good mechanical condition. This requires a check of the operation of all controls such as dials, dial mechanisms, switches, etc. A thorough inspection of all shielding should be made, determining that all necessary shields are installed and that all screws are secure.

3. Check all electrical features of the generator by operating the equipment. Determine that the output indicator functions and that the output level control functions over its full range. The generator should be tuned through its full frequency range to insure that output is available at all frequencies within the range. The attenuator should be checked through its full range. The internal modulation should be checked, including all associated controls and meters.

4. Select the most appropriate method to be used in calibration, after considering the functions of the particular generator and the equipment available for calibration purposes. Choose an appropriate output cable and load impedance, as determined by frequency range

and output impedance of the generator. Necessary fittings must be provided for connecting the load impedance and calibration equipment.

5. Check for signal leakage by any of the methods described and correct any defects which are discovered.

6. Determine the operational procedures recommended by the generator manufacturer. Following this procedure, adjust necessary controls to establish an indicated voltage or power of the maximum obtainable from the generator. Measure the output and correct measured values, if necessary, for the effects of signal generator, coaxial cable and load impedances to determine the true output level. If this does not agree with the calibration, adjust the internal calibrating controls until the correct value is indicated. This should be possible in all generators. Failure to obtain this agreement indicates that some component of the output indicator, such as bolometer, vacuum-tube diode, crystal rectifier, or meter, is probably defective. Replace such defective parts and repeat procedure.

7. Repeat the measurement of maximum output at selected frequencies throughout the frequency range. If the calibration is found to vary with frequency, attempt to obtain a compromise setting of the internal calibration controls which will result in an indicated output at any frequency which is accurate within the specified limits for the generator. If such a setting cannot be obtained, it is necessary to select a setting at one frequency and then obtain enough information to plot a correction curve of output versus frequency. Since the maximum calibrated output of almost all signal generators can be measured directly by use of a bolometer bridge, this method should be used in this step of calibration if possible.

8. Calibrate the attenuator in the signal generator. An appropriate method should be selected and the true output measured over as much of the attenuator range as permitted by the method. If errors are discovered and if the generator design permits, the attenuator scale should be adjusted to make true and indicated values correspond. However, such adjustment is usually not possible and a correction curve or chart must be obtained. Repeat the calibration at a number of selected frequencies to determine if a frequency correction is necessary.

9. If possible, correct the calibration controls of any manufactured signal generator which has been calibrated in the process of manufacture so that the indicated output is correct within the manufacturer's specified limits. By providing correction curves or tables as determined during recalibration, the accuracy of the generator should be improved, since the greatest deviation from the correct values are usually an effect of frequency.

Once a complete calibration has been obtained for a particular generator, the maintenance checks do not need to be as detailed. The maximum output should be measured at the extremes of each frequency range. The attenuator may be checked at several points in its range at one frequency. Unless these measured values differ significantly from the calibrated values, a full check is not required. This check of the calibration should be made at periodic intervals of not more than a few weeks and may be required more often depending on the amount of use of the generator between calibration. A check of calibration approximately once a month appears desirable, even though the generator may not have been used at all, since parts may deteriorate merely from age.

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